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Water Hyacinth Wastewater Treatment Systems: Opportunities and Constraints in Cooler Climates

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16. ABSTRACT

Aquatic plant wastewater treatment systems, mainly those involving water hyacinths, have been demonstrated to be cost-effective in warm areas of the U.S., such as southern Texas and Florida. However, no prior studies have been undertaken to systematically identify areas where cool temperatures would limit the use of such aquatic plant wastewater treatment systems. In this report, three geographic zones in the U.S. where various types of aquatic plant systems would be likely to provide reliable year-round treatment are identified. The coolest of these zones extends northward to a latitude of about 35°N. The costs of using greenhouse structures to extend the geographic range of effective treatment are evaluated. It is concluded that greenhouse construction and heating fuel costs would tend to increase total costs substantially above those for conventional treatment alternatives. Several potential legal and regulatory barriers to the use of aquatic plant wastewater treatment systems also are discussed. Finally, various concepts that may lead to the wider application of this innovative technology are identified.

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WATER HYACINTH WASTEWATER TREATMENT SYSTEMS: OPPORTUNITIES AND CONSTRAINTS IN COOLER CLIMATES

by

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1.0 INTRODUCTION

The U.S. Environmental Protection Agency (EPA) is responsible for evaluating grant applications for the construction of publicly owned treatment works under Section 201 of the Clean Water Act of 1977 (33 U.S. Code 1251, et seq.). As part of this mission, the EPA supports research leading to the development and operation of innovative and alternative technologies for municipal wastewater treatment. At a seminar sponsored by the EPA in 1979, it was concluded that certain aquaculture systems, particularly those utilizing water hyacinths, are ready for routine use in municipal wastewater treatment (Reed et al. 1979). However, certain problem areas were noted, including questions regarding the usefulness of water hyacinth systems in cooler climates, where the plant would not grow naturally, and the potential usefulness of other plant species in such regions. In a recent publication, Middlebrooks and Reed (1981) concluded that based on the limited data available, it appears that it would be uneconomical to develop a water hyacinth wastewater treatment system in cold regions. In general, there has been concern that a need for climate control using a greenhouse would increase the costs of aquatic plant systems to a point that they would be impractical.

1.1 Purpose of the Study

The broad purpose of this study was to evaluate the potential for using selected aquatic plant wastewater treatment systems in temperate or cooler regions of the U.S., based on the limited data currently available. Emphasis was placed on those selected species for which temperature tolerance information was available, principally, water hyacinth, duckweed, bulrushes, reeds and cattails. This study is intended as a preliminary evaluation, helpful in guiding research and development efforts. As current and anticipated projects yield new insights, the conclusions of this report may be refined or substantially altered.

1.2 Objectives of the Study

In general, this study was directed toward examining the major factors that could potentially limit the use of aquatic plant wastewater treatment systems in cooler climates. Specific objectives were:

- To identify the ecological limitations of systems without climate control, as represented by the temperature requirements of key plant species.
- To identify legal and institutional barriers to the increased use of aquatic plant wastewater treatment technology.

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- To undertake a preliminary evaluation of the economic feasibility of using aquatic plant systems in cooler climates.

- To identify concepts and approaches that might be helpful in overcoming any identified limitations.

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1.3 Approach

This study was initiated with a general information search. Three computerized bibliographic data bases were examined for relevant titles:

- AGRICOLA (Agriculture Online Access), produced by the National Agricultural Library of the U.S. Department of Agriculture, Washington, D.C.

- POLLUTION ABSTRACTS, produced by Cambridge Scientific Abstracts, Washington, D.C.

- WRA (Water Resources Abstracts), produced by the Water Resources Scientific Information Center of the U.S. Department of the Interior, Washington, D.C.

In addition to the computer-assisted search, several recent documents were reviewed for lists of references. Most important among these was the proceedings of a recent seminar sponsored by the EPA (Bastian and Reed 1979). Key investigators were contacted for information on the present status of their research.

Based upon the results of this first phase, the scope of this study was refined and specialized approaches were developed to meet project objectives. Efforts were focused on developing an approach for systematically identifying areas in the U.S. where aquatic plant wastewater treatment systems would provide reliable year-round treatment without climate control. As detailed in the following chapter, the relationship between air temperature and plant growth was selected as the key predictor of system performance. Generalized temperature data for the U.S. were used to map zones where various plant species would be expected to be effective in contaminant removal year-round, nine months out of the year, and six months out of the year.

The identification of legal and regulatory barriers mainly involved interviewing representatives of various Federal and state agencies. A detailed listing of personal communications is given at the end of the report. The preliminary evaluation of economic feasibility consisted of estimating the costs of using a greenhouse and evaluating the impact of these additional costs when compared to the costs of conventional treatment alternatives.

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1.4 Limitations

The development and implementation of an innovative wastewater treatment technology is a complex and dynamic process. This study addresses some of the key issues relating to aquatic plant treatment systems. However, it is subject to some important limitations:

- The analyses undertaken were intended to provide a broad overview. They would not provide definitive guidance for evaluating a specific proposal for the construction of an aquatic plant wastewater treatment facility.

- The technical information available for this technology area is limited. Sources included the available literature, contacts with researchers, government administrators, and some representatives of private firms active in this area. One site visit was made to the Disney World water hyacinth facility in Lake Buena Vista, Florida.

- This study is limited to municipal wastewater treatment applications. Potential industrial wastewater treatment applications are not addressed.

- Species analyses are limited to five types of higher aquatic plants commonly used in aquatic plant wastewater treatment systems. As research progresses in this technology area, other types of plants may prove equally or more suitable for cooler climate facilities.

- The approach used to map aquatic plant utility zones relies on the relationship between average daily air temperature and plant growth as a meaningful indicator of contaminant removal potential. As discussed in detail in the report, there are some important limitations associated with this approach.

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2.0 TEMPERATURE LIMITATIONS FOR SYSTEMS WITHOUT CLIMATE CONTROL

The effective treatment of municipal wastewater by aquatic plants is contingent upon the growth processes of the plants and an associated microbial community. A wide range of climatic factors influence plant growth rate and, thus, the effectiveness of aquatic plant treatment systems.* As discussed by Tchobanoglous et al. (1979b), these include seasonal averages and diel (daily) variations in air temperature, the average number of overcast days, local photoperiod, light intensity, the duration and intensity of rainfall, the strength and frequency of winds, and the probability of unseasonal weather. Temperature is apparently the single most important factor affecting aquatic plant growth. Specifically, Lee and McKim (1981) reported that air temperature was more closely correlated with water hyacinth yield than either water temperature or insolation.

In general, plants are productive between 5 and 40°C (Larcher 1975). However, individual species typically function best within some portion of this general range. When temperatures deviate from an optimum growth temperature, a reduction in treatment efficacy would be expected. Data collected at various demonstration facilities confirm that reduced treatment efficiencies do result when temperatures are either too high or too low for the cultured species. Accordingly, the climate at the wastewater treatment site has been recognized as the major factor in the selection of the aquatic species to be used for wastewater treatment (Tchobanoglous et al. 1979b).

In this chapter, the temperature requirements of various aquatic plant species were used to identify areas in the U.S. where particular types of aquatic plant systems could be used for year round wastewater treatment without climate control. Two types of floating aquatic plants, including the water hyacinth, and three types of emergent or wetland plants were the subjects of detailed examination. These species profiles were used in preparing a generalized map depicting zones where aquatic plant systems may be effective without the additional costs of a greenhouse. These generalized results were used as a basis for classifying the potential utility of a number of other aquatic plant species for which less information on temperature, growth, and waste treatment capability was available. The information presented in this chpater is subject to the limitations described in Section 1.4.

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*The associated microbial community may remain active in contaminant removal even though plants are not actively growing.

2.1 Mapping Methodology

The potential growth distribution pattern for various aquatic plant species was identified using two types of information. First, the literature was reviewed for data on temperature-growth relationships for each species. Stephenson et al. (1980) conducted a thorough review of this and other environmental requirements of aquatic plants. A second type of information used in preparing this analysis was normal daily average temperature data reported by the U.S. Department of Commerce (1979). These data were displayed by month as contour maps with a 5°F interval. The analysis for this section involved fitting the low temperature value for a particular species to the closest contour line shown for January, the coolest month of the year. The results indicate the zone in the U.S. where daily average air temperature is sufficiently warm for a species to grow year-round. The nine month (March-November) growth region was identified using the temperature map for March. The sixth month (May-October) was identified using the temperature map for October. The individual species maps were then used in synthesizing a generalized map showing aquatic plant utility zones.

Although this approach is useful in providing an overview, it does have several important limitations. First, as noted previously, in addition to temperature, a number of other climatic variables influence the contaminant removal efficiency of aquatic plants. Unfortunately, the information necessary to extend the analysis to these other variables is lacking. In addition to this limitation, the use of average daily air temperatures introduces some analytical error. Plants can be especially sensitive to diel variations in temperature. In some areas where average temperature values are suitable for plant growth, maximum or minimum values may preclude system use. In the southwestern deserts, for example, where average daily temperatures may be in accordance with plant requirements, wide temperature variations and high rates of evapotranspiration may necessitate the use of a greeenhouse. It also should be noted that the emphasis in this analysis on minimum temperature requirements for plant growth does not recognize areas where high temperatures may be a problem. Finally, it is recognized that the use of air temperature data may result in a conservative estimate of aquatic plant utility zones, since wastewater effluent temperatures may be warmer than ambient air temperatures.

2.2 Generalized Results

In general, results of the species analyses indicated that reliable year-round performance by aquatic plant wastewater treatment systems without climate control is likely only in southern portions of the continental U.S. and in Hawaii. Using the previously described approach for mapping plant growth regions, these areas were classified according to the temperature requirements of various types of aquatic plants. As shown on Figure 1, the following three plant specific "utility zones" were identified:

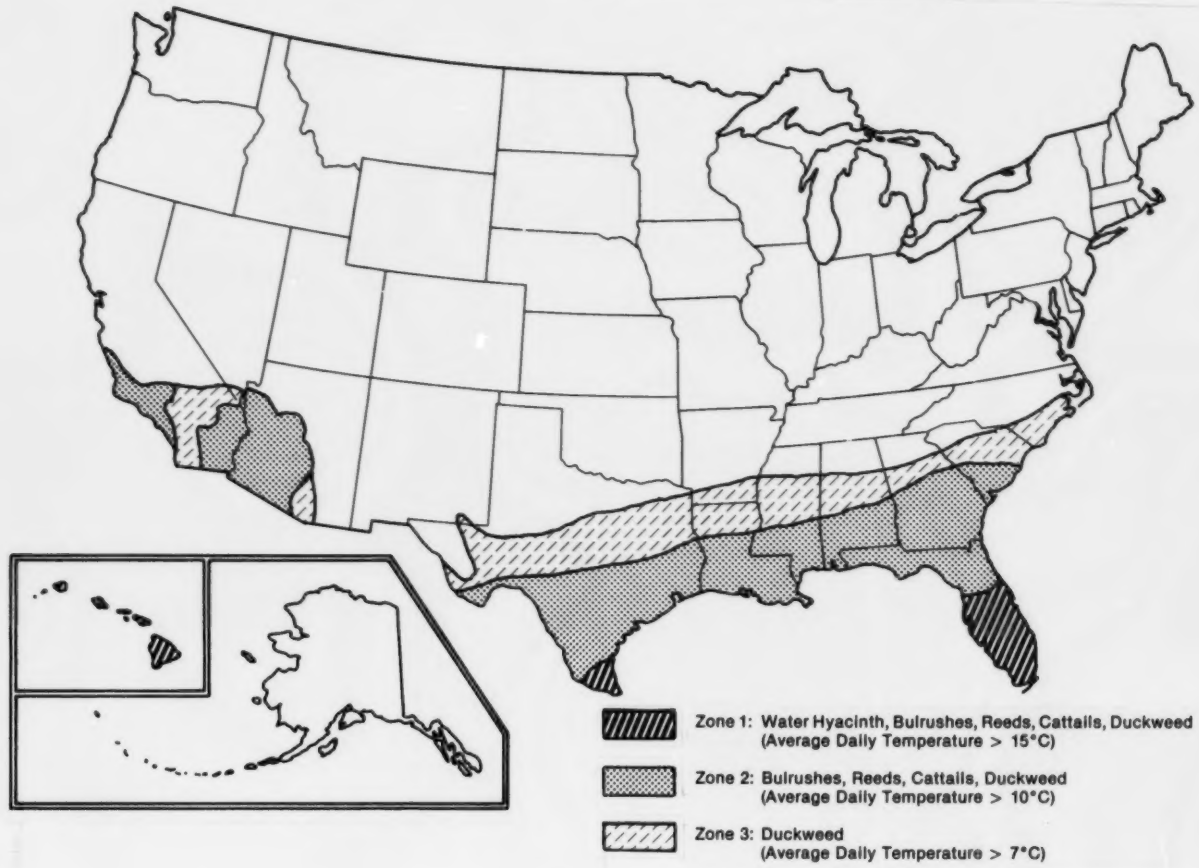
Zone 1: Water Hyacinth, Bulrushes, Reeds, Cattails, Duckweed
(Average Daily Temperature > 15°C)
Zone 2: Bulrushes, Reeds, Cattails, Duckweed
(Average Daily Temperature > 10°C)
Zone 3: Duckweed
(Average Daily Temperature > 7°C)

FIGURE 1
AQUATIC PLANT UTILITY ZONES FOR YEAR-ROUND WASTEWATER TREATMENT WITHOUT CLIMATE CONTROL

- Zone 1, which includes areas in the U.S. where the average daily air temperature is at least 15°C (59°F) year-round, would be suitable for effective use of any of the plants considered, including the sub-tropical water hyacinth.

- Zone 2, which includes areas in the U.S. where the average daily air temperature is at least 10°C (50°F) year-round, would be suitable for selected emergent or wetland species and for duckweeds.

- Zone 3, which includes areas in the U.S. where the average daily air temperature is at least 7°C (45°F) year-round, would be suitable for cold tolerant species of duckweed.

It should be emphasized that the three zones were identified based on available information on the temperature requirements of various plant species. In many cases, no studies that specifically focused on the relationship of temperature to growth rate could be identified. Thus, conclusions often were drawn from a body of supporting evidence in the literature, including general references to the natural distribution patterns of the selected species. Overall, the results of studies conducted at existing aquatic plant wastewater treatment facilities appear consistent with the results of the mapping procedure. There were, however, several specific areas where information was lacking: (1) contaminant removal efficiency of individual plant species in complex aquatic plant wastewater treatment systems such as those involving wetland habitats; (2) growth rates of cold-tolerant forms of plants such as duckweed; and (3) contaminant removal efficiencies resulting from the continued growth of some emergent plant rhizome systems (underground stems) at temperatures too low for growth of aerial portions of the plant. Additional information in these areas would be necessary to more accurately define the boundaries of aquatic plant utility zones.

2.3 Selected Species Profiles

In this section, the temperature requirements of key aquatic plant species were used to identify regions in the U.S. where these plants might be effective in nutrient removal. Climate control, typically involving the use of greenhouse structures, is intended to extend the range of system utility beyond natural limitations. However, the general purpose of this section is to establish baseline conditions, or utility under natural circumstances, for plants commonly used in wastewater treatment applications. Based on a review of the literature, the following aquatic plants were selected for detailed analysis:

- Floating Aquatic Plants: Water hyacinth
  Duckweed

- Emergent Aquatic Plants: Bulrushes
  Reeds
  Cattails

2.3.1 Floating Aquatic Plants

Floating aquatic plants usually grow on the water surface and are not attached to bottom substrates. This classification includes such plants as water hyacinth, water lettuce, water fern, duckweed and alligatorweed. Under some conditions, floating aquatics can become a major nuisance in the natural environment. Some species form dense mats, which may impede navigation and reduce levels of dissolved oxygen necessary for maintaining of aquatic animal communities. Many of these nuisance species reproduce vegetatively, a process where a piece of an existing mat can give rise to a new stand of plants. Thus, populations may spread rapidly throughout irrigation and drainage systems. Although they are found in a range of aquatic environments, they are most common in slow moving and stagnant freshwater lakes, ponds and ditches.

Much of the research that has been carried out on the use of aquatic plants for wastewater treatment has focused on floating species, mainly water hyacinth. Water hyacinth systems have been shown to be effective in meeting both secondary and advanced treatment standards (Middlebrooks and Reed 1981). Floating aquatic plant systems also have been shown to be effective in removing algae, fecal bacteria and odor-causing compounds (National Research Council 1976).

Although most floating aquatic plant wastewater treatment systems have been located in warmer areas, a number of studies conducted at these sites have provided valuable information on the effects of cooler temperatures on system performance. As discussed below, evidence indicates that consistent treatment performance by water hyacinth systems would be likely only in the very warmest regions of the U.S. The potential for duckweed systems has not been tested as extensively. However, preliminary indications are that cold tolerant forms of duckweed may have utility at average daily temperatures as low as 5 to 10°C.

2.3.1.1 Water Hyacinth. Water hyacinth (Eichhornia crassipes) is the floating vascular plant most commonly used in aquaculture wastewater treatment systems. These plants respond exceptionally well in a nutrient-enriched aquatic medium (Ryther et al. 1979). As a result of a number of demonstration projects in warmer climate states, it was concluded that such systems are ready for routine use for municipal wastewater treatment in the geographical range where water hyacinths grow naturally (Reed et al. 1979). As summarized by Middlebrooks and Reed (1981), such systems can be used to treat raw wastewater as well as effluents from other municipal wastewater treatment process stages. The most common system type incorporates a stabilization pond followed by a series of water hyacinth culturing tanks or raceways. As shown on Table 1, using recently developed design criteria, these systems can produce an advanced secondary effluent.

The water hyacinth is a free-floating freshwater plant distinguished by bright green, shiny or polished appearing leaves (Weldon et al. 1973). Plant size varies with habitat, leaf length ranging from 8 to 127 cm.

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TABLE 1

DESIGN CRITERIA FOR WATER HYACINTH WASTEWATER TREATMENT SYSTEMS

Parameter	Design Value		Expected Effluent Quality
	Metric	English	
RAW WASTEWATER SYSTEM			$BOD_5 \leq$ 30 mg/l SS $\leq$ 30 mg/l
Hydraulic residence time	>50 days	>50 days	
Hydraulic loading rate	200 m^3/ha·day	0.0214 mgad	
Depth, maximum	$\leq$1.5 m	$\leq$5 feet	
Area of individual basins	0.4 hectare	1 acre	
Organic loading rate	<30 kg BOD_5/ ha·day	<26.7 pound BOD_5/ac·day	
Length to width ratio of hyacinth basin	>3:1	>3:1	
Water temperature	>10°C	>50°F	
Mosquito control	Essential	Essential	
Diffuser at inlet	Essential	Essential	
Dual systems, each designed to treat total flow	Essential	Essential	
SECONDARY EFFLUENT SYSTEM			
			$BOD_5 \leq$ 10 mg/l SS $\leq$ 10 mg/l TP $\leq$ 5 mg/l TN $\leq$ 5 mg/l
Hydraulic residence time	>6 days	>6 days	
Hydraulic loading rate	800 m^3/ha·day	0.0855 mgad	
Depth, maximum	0.91 m	3 feet	
Area of individual basins	0.4 hectare	1 acre	
Organic loading rate	<50 kg BOD_5	<44.5 pound BOD_5/ac·day	
Length to width ratio of hyacinth basin	>3:1	>3:1	
Water temperature	>20°C	>68°F	
Mosquito control	Essential	Essential	
Diffuser at inlet	Essential	Essential	
Dual systems, each designed to treat total flow	Essential	Essential	
Nitrogen loading rate	$\leq$15 kg TKN/ ha·day	<13.4 pound TKN/ac·day	

Source: Middlebrooks and Reed 1981.

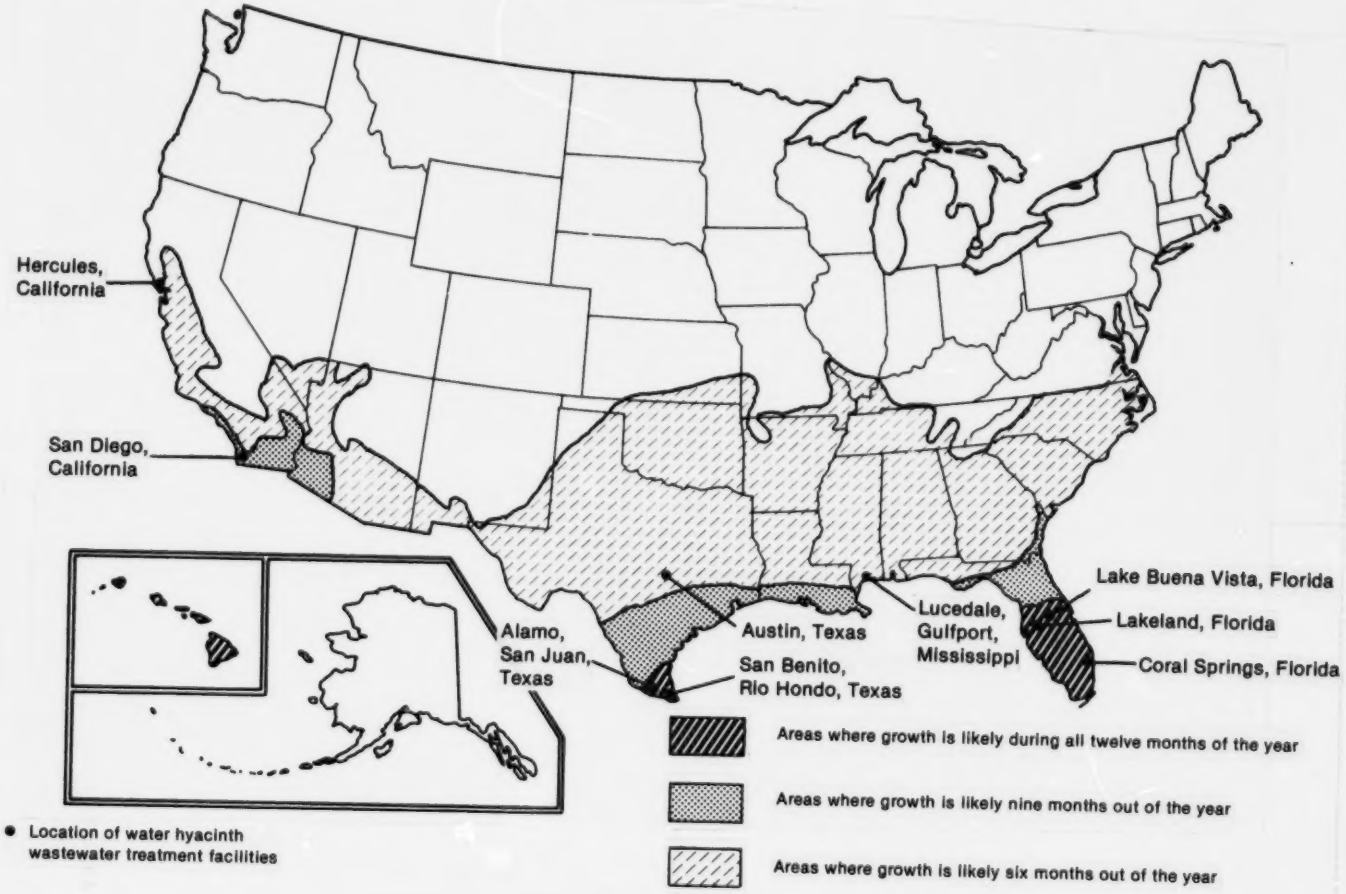
Reproduction occurs mainly by vegetative means, although a large number of seeds also are produced. Water hyacinth is considered one of the most productive plants on earth (Ryther et al. 1979). Under optimal culture conditions, the annual daily mean value for primary production was reported as 24.2 g(dry wt)/m^2/day. As noted by Robinson et al. (1976), total plant mass can double within a few weeks under favorable conditions.

Air temperature requirements of water hyacinths were reviewed by Stephenson et al. (1980). They found that water hyacinths were reported to survive 24-hour exposure to air temperatures ranging from 0.5 to -5°C, but die at -6 to -7°C and cannot become established in regions where winter temperatures average 1°C. Freezing and subsequent withering of leaves cause underwater parts to float nearer the surface, increasing exposure to freezing air temperatures. Growth has been found to be rapid at 20 to 30°C and nearly stops at 8 to 15°C.

Water temperatures of 34 to 40°C were reported to be lethal to water hyacinths within two to three weeks (Stephenson et al. 1980). Growth was most rapid at 28 to 30°C and fell precipitously at temperatures above 30°C. Temperatures of surface water within plant mats were found to be higher in winter and lower in summer than temperatures in open water.

An average daily temperature of 15°C (59°F) was selected as the minimum reference temperature for water hyacinth growth. Using the approach described previously, the potential growth distribution pattern for this species was determined. As shown on Figure 2, only three regions where water hyacinths would be likely to grow year round without climate control were identified. They are: southern Florida, the southern tip of Texas, and Hawaii. In these areas it would be expected that nutrient removal performance could be maintained at levels sufficient to meet the effluent treatment standards for which the system was designed. In contrast, it would be expected that periodic performance failures due to cool temperatures would occur at water hyacinth systems located outside the year-round growth region.

Most of the existing water hyacinth wastewater treatment facilities are located within the year round growth regions. Although treatment efficiency data from existing facilities are limited, there is some evidence of the effect of temperature on system performance. Lee and McKim (1981) reported that cold temperatures during January and February 1981 reduced treatment efficiences at the 63,000 gallons per day prototype water hyacinth wastewater treatment system at Walt Disney World in Lake Buena Vista, Florida. However, other problems affecting the system at the same time made it impossible to quantify the amount of efficiency loss that could be attributed to cold temperatures. A greenhouse type cover will be installed this winter over one of three channels at the Lake Buena Vista facility (Lee and McKim 1981). It is notable that cold temperature problems occurred even though this operation is located within the calculated year round growing region.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San Diego, California
Alamo, San Juan, Texas
Austin, Texas
San Benito, Rio Hondo, Texas
Lucedale, Gulfport, Mississippi
Lake Buena Vista, Florida
Lakeland, Florida
Coral Springs, Florida
Areas where growth is likely during all twelve months of the year
Areas where growth is likely nine months out of the year
Areas where growth is likely six months out of the year
• Location of water hyacinth wastewater treatment facilities

FIGURE 2
POTENTIAL GROWTH DISTRIBUTION PATTERN FOR WATER HYACINTH *(Eichhornia crassipes)*

At another facility, the Williamson Creek Experimental Hyacinth Treatment System in Austin, Texas, cold temperatures during winter months have resulted in some loss of plants, overall reductions in plant growth and attendant declines in nutrient uptake (Dinges, personal communication). As a result of such experiences, Dinges (1979) concluded that continuous culture of water hyacinths in open basins in Texas is feasible only in the sub-tropical climate of the Lower Rio Grande Valley.

Cold temperatures also created problems at several experimental facilities in southern Mississippi. As described by Wolverton (1979), freezing temperatures killed the tops of water hyacinth plants, and the decay of this biomass elevated the biochemical oxygen demand (BOD) and total suspended solids (TSS) levels in the effluent during January, February and March. Recent studies conducted by the National Space Technology Laboratories (NSTL), National Aeronautics and Space Administration (NASA), NSTL Station, Mississippi have focused on more cold-tolerant species (Wolverton, personal communication).

2.3.1.2 Duckweed. Following water hyacinth, duckweed is probably the most frequently discussed candidate for aquatic plant wastewater treatment systems. However, duckweeds actually have been employed in very few demonstration facilities. Consequently, there is little information available on the nutrient removal performance of these plants relative to temperature. Also, the term duckweed refers to a family of plants, which consists of four genera and numerous species. The forms vary widely with regard to environmental requirements; and this variability makes it difficult to draw general conclusions based on the limited information available.

The duckweeds are among the smallest (maximum length of 1.5 cm) and simplest of flowering plants. As noted previously, the duckweed family (Lemnaceae) consists of four genera. These are: Spirodella, Lemna, Wolffiella, and Wolffia. Instead of distinct leaves and stems, these plants have a simplified plant body (frond), which represents a fusion of the two. Reproduction is by budding and seed in most species. Duckweeds are widely distributed; some strain of one or more Lemnaceae species occurs in all climatic regions except entirely waterless deserts and, perhaps, the tundra (Hillman and Culley 1978). The growth rate of duckweed undoubtedly varies from one strain to another. However, the literature indicates that duckweed is far less productive than water hyacinth, even under favorable conditions. Ryther et al. (1979) reported an annual daily mean yield for common duckweed (Lemna minor) of 3.7 g(dry wt)/m^2/day. Values for duckweed (species not given) reported by Hillman and Culley (1978) are slightly higher, but roughly comparable to the 3.7 figure.

The effects of temperature on duckweed growth are difficult to define because of the wide variability in the requirements of various forms. In their reviews of the literature, Hillman and Culley (1978) and Stephenson et al. (1980) noted that some duckweed species have been reported to grow at near freezing temperatures. Harvey and Fox (1973) cited a study in the

Soviet Union where a strain of common duckweed (Lemna minor) was found to grow at temperatures as low as 1°C. Hillman and Culley (1978) indicated that a duckweed strain that would grow rapidly at 5 to 10°C could be identified through a selection program.

A minimum reference temperature of 7°C (45°F) was selected for the purpose of identifying the potential growth regions for duckweeds. As shown on Figure 3, much of the southern U.S. lies within the region where year-round growth would be predicted. Further, it was found that duckweeds would be likely to grow at least six months out of the year across most of the U.S.

As previously noted, there are few field data available that could be used to confirm the theoretical boundaries of the duckweed utility zone developed in this report. However, the available literature is not inconsistent with the findings of the theoretical approach. In one small-scale field study conducted in Fort Pierce, Florida, Ryther et al. (1979) found that while yields of duckweed are substantially lower than those for water hyacinth, they are less subject to variation due to cooler winter temperatures (Figure 4). Studies in southern Mississippi indicate that detention times for duckweed lagoons must be longer than those for water hyacinth lagoons to achieve the same contaminant removal efficiences (Wolverton 1979). However, while cold temperatures adversely affected the water hyacinth systems, no such problems were reported for the duckweed facility. Research conducted at the Cardiff AquaCell Demonstration Laboratory, in the San Diego, California area, showed that the use of duckweeds (Lemna sp.) in place of water hyacinths resulted in slightly decreased treatment efficiences, indicating that a 20 to 30 percent increase in detention time would be required to achieve the same treatment objectives (Stewart and Serfling 1979). It also was noted that duckweed could be used for advanced treatment in the southern U.S. without a greenhouse cover.

2.3.2 Emergent Aquatic Plants

Emergent aquatic plants are erect, herbaceous hydrophytes rooted in saturated soil or soil covered with water, with most of the plant body occurring above the water surface. This classification includes cattails, reeds, rushes, sedges and aquatic grasses. Often referred to as wetland species, emergent aquatic plants are found in virtually all types of fresh and brackish water environments.

A substantial amount of research has been carried out on the use of emergent plants for wastewater treatment. Many of the pioneering studies were conducted in West Germany (Seidel 1976). In the U.S., most studies have involved the use of associations of various emergent species in a natural or artifical wetland setting (Reed et al. 1979). Although such mixed culture systems generally have been successful, their complexity makes it difficult to address the effectiveness and cold-temperature tolerances of individual species. In addition, many of the studies on emergent aquatic plants have focused on effluent treatment only during the summer months.

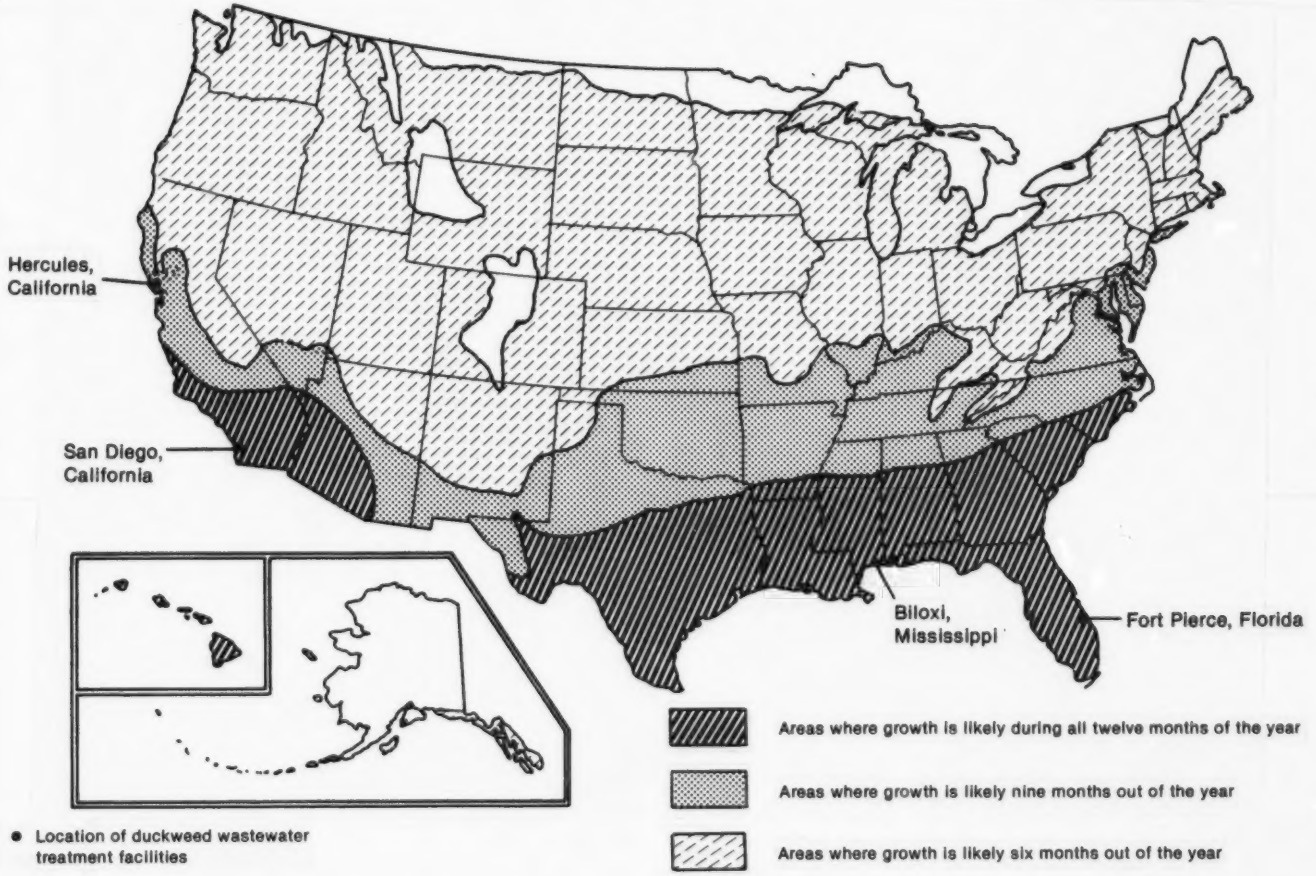
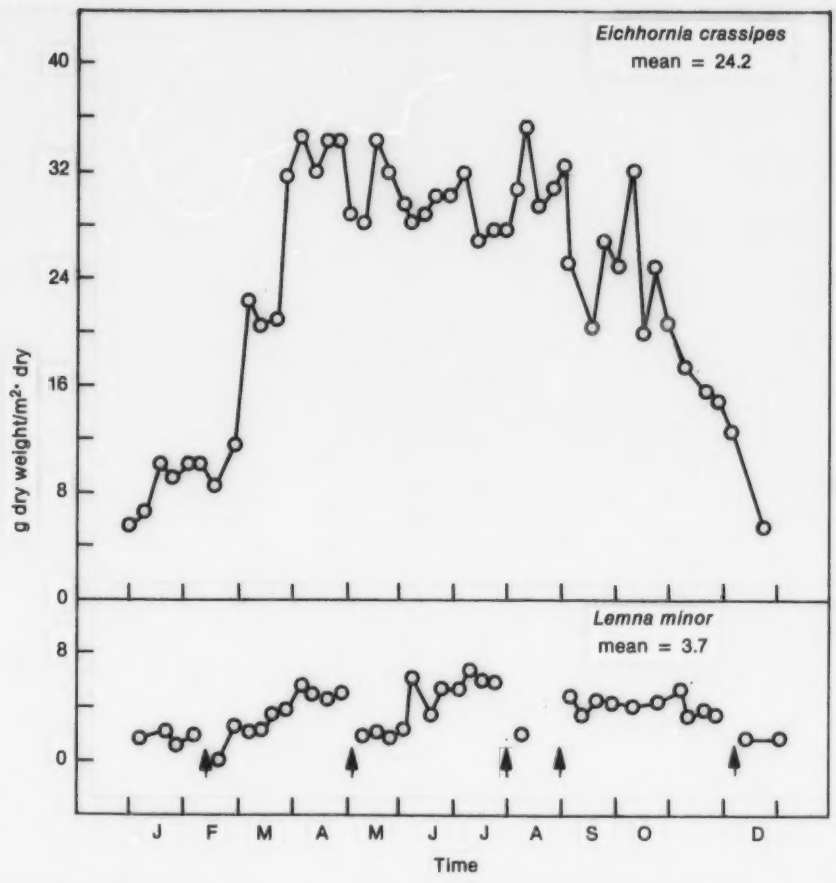

Hercules, California
San Diego, California
Biloxi, Mississippi
Fort Pierce, Florida
Areas where growth is likely during all twelve months of the year
Areas where growth is likely nine months out of the year
Areas where growth is likely six months out of the year
• Location of duckweed wastewater treatment facilities

FIGURE 3
POTENTIAL GROWTH DISTRIBUTION PATTERN FOR DUCKWEED
(Lemnaceae)



Note: Arrows in *Lemna* Figure Indicate Times When Culture Became Overgrown with Epiphytic Algae or Was Blown Out of Pond by High Winds and Had to be Restarted

Source: Rhyther et al. 1979

FIGURE 4
ANNUAL YIELDS OF WATER HYACINTH *(Eichhornia crassipes)*, AND DUCKWEED *(Lemna minor)*, AT FORT PIERCE, FLORIDA

Thus, the effects of cooler temperatures on the performance of various species are not well documented.

Recent studies conducted by NASA indicate that some emergent aquatic plants may be capable of contaminant removal at cooler temperatures (Wolverton, personal communication). As discussed later in this section, it has been suggested that the extensive underground portion of emergent plants such as the common reed (Phragmites australis) continues to grow, and thus to remove contaminants, at temperatures too low for growth of above ground portions of the plant.

2.3.2.1 Bulrushes. Bulrushes (genus Scirpus) have been used for wastewater treatment in both highly controlled aquaculture facilities and in wetland type systems. A patented process developed at the Max Planck Institute in West Germany created substantial interest in the potential use of these plants for wastewater treatment. The design has been used in the construction of at least two prototype operations, one in the Netherlands and one in California. However, as discussed below, no studies that focused on treatment efficiency at cooler temperatures could be identified. Thus, estimates of the potential utility of bulrushes in the upper U.S. are based on natural distribution patterns and limited data on temperature-growth relationships.

The genus Scirpus includes about 150 species within the U.S. (Muenscher 1944). In general, they are characterized as being rush-like, with triangular or terete stems. Typically, species considered as candidates for wastewater treatment are those with thick, creeping rhizomes (underground stems). As identified by Stephenson et al. (1980) these include: Scirpus americanus, S. californicus, S. fluviatilis, S. lacustris, S. maritimus, S. microcarpus, S. olneyi, S. subterminalis and S. validus. These are described as species with erect shoots that are 0.3 to 3 m tall, having a subterminal inflorescence (aggregation of flowers) composed of 3 to 15 stalks, each bearing one or more spikelets. Reproduction is by both seed and vegetative means. Bulrushes are found in the shallow zones (saturated soils and open water up to 3 m deep) of a variety of freshwater and brackish aquatic habitats. Distribution of the genus is worldwide, with representatives occurring throughout the continental U.S. (Muenscher 1944).

Although the capability of bulrushes to purify wastewater has been well demonstrated (de Jong 1976; Seidel 1976), very little research has been directed toward determining the effects of temperature on contaminant removal efficiency. Stephenson et al. (1980) cite a study which involved examining the capability of bulrushes to absorb phosphate over a range of soil temperatures. It was found that one cool-temperate species of bulrush had an optimum soil temperature for root production of 10°C; phosphate absorption by some plants increased with decreasing temperature at temperatures above 1°C. It is notable that after reviewing the literature, Stephenson et al. (1980) concluded that the minimum average daily air temperature for bulrush growth is about 17°C. Differences between this estimate and the 10°C value were not reconciled, although the higher value may pertain to aerial portions of bulrush plants.

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In contrast to the findings of Stephenson et al. (1980), it was concluded in this study that a daily average air temperature of 10°C (50°F) may be more appropriate minimum reference value for bulrush growth. This conclusion was based on the limited information available for temperate species of Scirpus and a comparison of the natural distribution patterns for these and other emergent plant species for which more temperature-growth data are available (see following sections). Based on the 10°C value and using the previously described approach, zones of potential utility of bulrush systems without climate control were identified. As shown on Figure 5, four regions where bulrushes would be likely to grow year round were identified. They are: a southern U.S. region, including all of Florida and portions of South Carolina, Georgia, Alabama, Mississippi, Louisiana, and Texas; southern California; western Arizona; and the Hawaiian Islands. In these areas, it would be expected that consistent contaminant removal performance could be maintained. Outside these areas, performance problems resulting from cold temperatures would be expected.

Bulrushes have been used in two types of wastewater treatment operations: a highly controlled patented process developed by the Max Planck Institute of West Germany, and wetland-type treatment systems. The German approach has been applied both in a recreational community setting in the Netherlands (de Jong 1976) and at a facility in Laguna Niguel, California (Pope 1981). While both operations confirmed that species of Scirpus were effective in contaminant removal, neither involved field testing at cooler temperatures. A similar system involving the planting of Scirpus validus on gravel beds was tested in Seymour, Wisconsin. Results of a water quality monitoring program indicated that most of the purification processes (ie., BOD removal and nutrient retention) were carried out in the gravel substrate system rather than by the vascular plants (Spangler et al. 1976). The authors also found that nutrients were released by the system following frost periods, leading to the conclusion that emergent plant systems would not be effective in northern latitudes. However, temperature data were not reported in conjunction with the results of water quality monitoring tests. Thus, the specific relationship between temperature and treatment efficiency was undefined. It is notable that the Seymour, Wisconsin site is located near the boundary of the estimated six-month growing region for bulrushes (Figure 5). As noted previously, performance failures resulting from cooler temperature would be expected in this area.

Many studies involving the use of wetlands for wastewater treatment do not give an accounting of the plant species present at the site. One study where bulrushes (Scirpus spp.) were among the species identified was conducted at a full-scale artificial wetlands treatment project near Martinez, California. This project involved pumping sewage effluent, treated to secondary standards, into a 20.3 acre (8.2 ha) wetland to improve on effluent quality and to enrich the existing wetland habitat (Demgen 1979). Water quality monitoring studies indicated that nitrate removal within the wetland was consistent year round; BOD and SS removal were seasonal. The author stresses that BOD and SS levels were mostly attributable to the export of algae and other products, typical of natural wetland dynamics.

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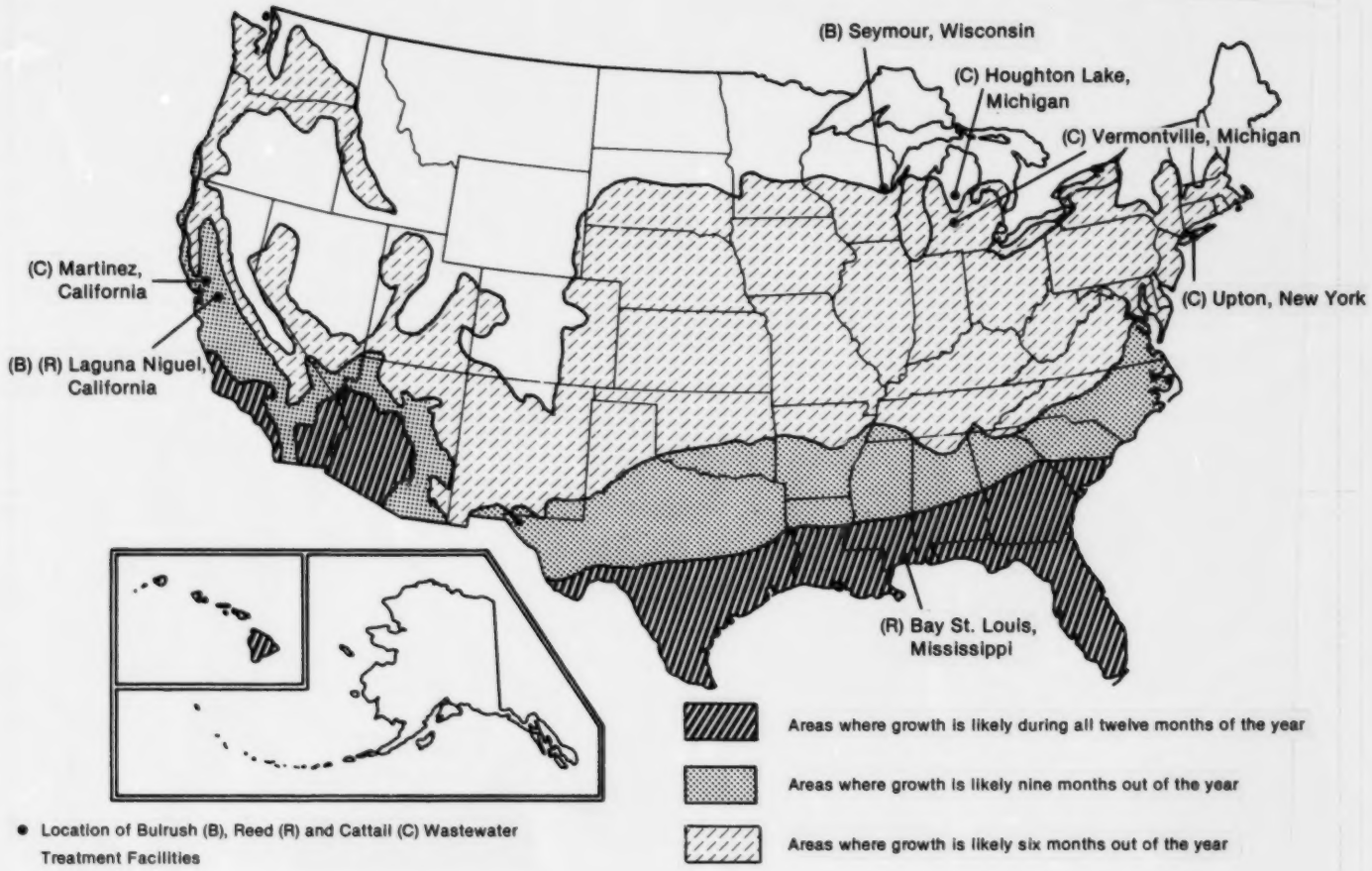
(B) Seymour, Wisconsin
(C) Houghton Lake, Michigan
(C) Vermontville, Michigan
(C) Martinez, California
(C) Upton, New York
(B) (R) Laguna Niguel, California
(R) Bay St. Louis, Mississippi
Areas where growth is likely during all twelve months of the year
Areas where growth is likely nine months out of the year
Areas where growth is likely six months out of the year
• Location of Bulrush (B), Reed (R) and Cattail (C) Wastewater Treatment Facilities

FIGURE 5
POTENTIAL GROWTH DISTRIBUTION PATTERN
FOR BULRUSHES, REEDS, AND CATTAILS

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2.3.2.2 Reeds. Although there are several species of reeds (family Poaceae), one species, the common reed (Phragmites australis), mainly is associated with wastewater treatment applications. The common reed is a tall (up to 4.5 m) perennial grass with an extensive rhizome system (Tarver et al. 1978). Reproduction occurs primarily by seed, but growth from rhizomes is common. As summarized by Stephenson et. al. (1980), the literature indicates that the common reed grows best in swampy soils covered with 60 to 80 cm of water. Although restricted to areas of gentle water movement, this species tolerates a wide variety of water quality, soil and climate conditions. Consequently, the common reed is abundant in many areas of the world. It occurs in fresh and brackish waters throughout the U.S., with the exception of some southeastern states.

As discussed by Stephenson et. al. (1980), the effects of temperature on reeds are known mainly from observations of seasonal and geographic differences in natural populations. In temperate regions aerial shoots die back in cooler months, although an underground system of rhizomes continues to grow during these periods. From the limited data on temperature ranges for the growing season of Phragmites, Stephenson et. al. (1980) estimated that 11°C is the lower daily average air temperature limit for plant growth. It was not noted whether this value applies to the aerial or rhizome portions of the plant.

An average daily temperature of 11°C (52°F) was selected as the minimum reference temperature for common reed growth. It is important to note that this value may be overly conservative, since rhizome growth may continue at lower temperatures. Thus, the growth distribution pattern developed for this report may underestimate the potential utility of the common reed for wastewater treatment in cooler climates. As shown earlier on Figure 5, four regions where the common reed would be likely to grow year round without climate control were identified. They are: a southern U.S. region, including all of Florida and portions of South Carolina, Georgia, Alabama, Mississippi, Louisiana, and Texas; southern California; western Arizona; and the Hawaiian Islands. In these areas, it would be expected that consistent nutrient removal performance could be maintained. Outside these areas, performance problems due to cold temperatures would be expected.

Field studies and pilot operations have shown that the common reed is capable of purifying wastewater. Seidel (1976) reported that Phragmites beds were effective in adjusting pH, increasing effluent transparency, and reducing levels of BOD and SS. In addition, there were indications that root excretions of several emergent plant species, including Phragmites, were effective in killing pathogenic bacteria in contaminated water. Based largely on Seidel's work, the Dutch government constructed a prototype emergent plant system for the treatment of sewage effluents from a summer camping site. Based on studies at this facility, it was concluded that small systems using the common reed, in conjunction with beds of the bulrush Scirpus lacustris can be more cost effective than conventional chemo-mechanical treatment plants for removing criteria pollutants (de Jong 1976). Unfortunately, this system was only tested during the summer months. Thus, no data were available on the effects of cooler temperatures on

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system performance.

In the U.S. one operation that expressly involved Phragmites was identified. This is a new Hybrid Wastewater Treatment System designed and operated by personnel from the National Space Technology Laboratories of NASA. Located in Bay St. Louis, Mississippi, the system combines anaerobic filters with a trough system planted with Phragmites. As discussed by Wolverton (1981), preliminary results show that the hybrid system creates a synergistic effect, increasing the treatment efficiency of both components. It was also concluded that the performance of a Phragmites system may be more consistent than water hyacinth systems at cooler temperatures. However, no data indicating the relationship between temperature and treatment efficiency were provided.

In addition to the NASA facility in southern Mississippi, some wetlands operations in the U.S. may involve the use of Phragmites in conjunction with other species. However, many of the studies on wetlands, especially those that are naturally occurring, do not include a list of species present. In addition, the complexity of most natural wetland systems makes it difficult, if not impossible, to determine the treatment capability of a single species under various temperature conditions.

2.3.2.3 Cattails. Cattails (genus Typha) have been used in a number of wetland wastewater treatment systems. However, little information is available on the treatment capabilities or the cold-tolerance of these plants. Limited 48-hour studies conducted by Wolverton (1980) showed that treatment efficiency by a cattail system was roughly comparable to that of a water hyacinth system at temperatures between 18 and 19°C. There also are some indications that cattails would be effective in wastewater treatment in cooler climates. The natural distribution of cattails extends into the northern U.S. Like the common reed, cattails have an extensive rhizome system, which may be effective in contaminant removal at cooler temperatures.

Four species of cattail are found in the U.S.: Typha domingensis, T. glanca, T. angustifolia, and T. latifolia (Weldon et al. 1973). They are tall, erect perennials, recognized by the reddish-brown or dark brown spikes of densely packed seeds which top jointless stems. The spongy leaves are flat to slightly rounded and vary in width from 3 to 8 mm in T. angustifolia (narrow leaved cattail) to 6 to 23 mm in T. latifolia (common cattail). A system of underground stems (rhizome) spreads extensively, so that a stand of cattails covering an acre may actually consist of only a few plants (Fassett 1940). In a review of the literature, Stephenson et al. (1980) found reports that rhizomes grow about 100 cm/year, any may comprise 45 to 60 percent of live plant biomass. Cattails are common in shallow bays, irrigation ditches, lakes, ponds and rivers, in both fresh and brackish water. As noted by Muenscher (1944), these are among the most cosmopolitan of aquatic plants. Two species, T. latifolia and T. angustifolia were reported to occur in most states in the continental U.S.

As discussed by Stephenson et al. (1980) the extensive distribution of T. latifolia and T. angustifolia indicates a wide range of temperature

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tolerance. However, as found by these authors, little information has been reported on the growth characteristics of cattails at different temperatures. Dykyjova et al. (1972) and Wolverton (1980) reported that cattails grew well at greenhouse temperatures of 20°C and 18.3°C, respectively. Stephenson et al. (1980) found reports that the optimum water temperature for growth of T. latifolia is 30°C, although survival was poor at 35°C. A study by McNaughton (1975) indicated that growth-temperature relationships may vary widely among cattail populations. Populations in cooler climates exhibited faster growth and development rates than those in warmer climates.

Based on the limited information available, Stephenson et al. (1980) concluded that an average daily temperature of about 9°C is the lower limit for the cattail growing season. Although a careful selection program could result in the identification of a strain that would grow at cooler temperatures, the 9°C (48.2°F) value is considered a reasonable estimate for the purposes of this report. Accordingly, the potential growth distribution pattern for cattails follows that identified for reeds (Figure 5). However, as in the case of the common reed, cattail rhizome systems continue to grow at cooler temperatures. Thus, this figure may underestimate the potential utility of these plants for wastewater treatment in cooler climates.

In cases where cattails have been used in wastewater treatment, system design has been based on either the natural or simulated marsh approach. In the Mt. View Sanitary District, located near Martinez, California, sewage effluent treated to secondary standards was discharged into an artificial wetland composed of 72 macrophyte species, including Typha spp. (Demgen 1979). Water quality monitoring showed that the wetland community was effective in reducing BOD and suspended solids levels during winter months, although water temperatures did not fall below 5°C. In another case, secondary wastewater was discharged into a central Michigan natural peatland (Houghton Lake), which supports a variety of emergent species, including Typha latifolia (Kadlec 1979). Water quality monitoring indicated that the cattail cover type was not as effective as other cover types in reducing levels of contaminants, such as nitrogen and phosphorus. However, differences in hydrologic conditions within the wetland may have been an important factor affecting treatment performance. Since the operation was designed to accommodate the treatment needs of a summer resort community, potential for treatment during cooler months was untested. In a third case, a municipal wastewater treatment system in Vermontville, Michigan was expanded to include discharge into an artificial wetland to reduce phosphorus levels (Williams and Sutherland 1979). Phosphorus levels were not reduced in surface water samples collected in the wetlands, but were markedly reduced in groundwater samples. From this, the authors concluded that the wetland vegetation, which included cattails, was an incidental factor in the treatment process. Although field testing was conducted on a year-round basis, no information was provided on the relationship between temperature and treatment efficiency. The final case identified is the prototype marsh/pond sewage treatment facility that was designed and operated by personnel from the Brookhaven National Laboratory in Upton, New York. As described by Small (1976), one element of this multi-phase artificial system was the passage of sewage and septage through a shallow cattail marsh. Several problems associated with the marsh design were

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noted, including difficulties in maintaining the cattail population. Although the entire system was reportedly successful in treating wastewater on a yearround basis, no data were provided on the effects of cooler temperatures.

2.4 Expanded List of Potentially Useful Aquatic Plants

Although the three zones identified in this report were based on the requirements of aquatic plants commonly used at existing facilities, a number of other aquatic plant have been discussed as potential candidates for wastewater treatment applications. Based on information compiled by Stephenson et al. (1980), an expanded list of plants potentially suitable in the three temperature zones was developed. As shown in Table 2, available information indicates that most candidate aquatic plants could be effectively used in Zone 1 and Zone 2 areas. A few aquatics, such as cordgrass and elodea, may be suitable for wastewater treatment applications in the slightly cooler Zone 3 areas.

85/8+6 3/8

TABLE 2

LIST OF AQUATIC PLANTS POTENTIALLY USEFUL FOR YEAR ROUND WASTEWATER TREATMENT IN VARIOUS TEMPERATURE ZONES

Aquatic Plant	TEMPERATURE ZONES*		
	Zone 1 15°C (59°F)	Zone 2 10°C (50°F)	Zone 3 7°C (47°F)
FLOATING AQUATIC PLANTS			
Water Hyacinth *Eichhornia Crassipes*	•		
Duckweeds *Spirodella spp., Lemna spp. Wolffiella spp., Wolffia spp.*	•	•	•
EMERGENT AQUATIC PLANTS			
Bulrushes *Scirpus spp.*	•	•	
Reeds *Phragmites spp.*	•	•	
Cattails *Typha spp.*	•	•	
Rushes *Juncus spp.*	•	•	
Sedges - Carex *Carex spp.*	•	•	
Sedges - Nutsedges *Cyperus spp.*	•	•	
Canarygrass *Phalaris spp.*	•	•	
Cordgrass *Spartina spp.*	•	•	•
SUBMERGED AQUATIC PLANTS			
Pondweed *Potamogeton spp.*	•	•	
Elodea *Elodea spp.*	•	•	•
Coontail *Ceratophyllum spp.*	•	•	
Watermilfoil *Myriophyllum spp.*	•	•	

*Based on average daily air temperatures for January

3.0 LEGAL AND REGULATORY ISSUES

A wide range of Federal and state statutes and regulations apply to municipal wastewater treatment. In their reviews of legal issues pertaining to aquaculture systems for wastewater treatment, Eichbaum (1976) and Lohman (1979) concluded that this complex regulatory framework creates problems in implementing innovative technologies. The three major issues addressed below are: attitudes toward aquatic plant wastewater treatment technology; effluent regulations; and regulations pertaining to the use, sale and transport of exotic plants. Analysis focused on regulations and policies at the state level as described by agency personnel from five randomly selected temperate or cooler climate states: California, Illinois, Kentucky, New York and Pennsylvania.

3.1 Attitudes Toward Aquatic Plant Wastewater Treatment Technology

There are a number of institutional problems associated with the diffusion of any innovative technology, especially where implementation depends upon permits and grants. As discussed by Eichbaum (1976), regulatory authorities tend to ignore the opportunities of a new technology in favor of the known results of an established control program. Since public monies are usually involved in building and operating wastewater treatment facilities and the objective of such programs is to ensure the protection of public water resources, such reluctance to assume risk is understandable.

In addition to this predisposition, Eichbaum (1976) noted that most regulatory offices lack personnel with the kinds of training that would permit an adequate evaluation of the concepts and opportunities inherent in an innovative wastewater treatment technology. Lohman (1979) added that adequate evaluation of an innovative wastewater treatment alternative is made more difficult because of the myriad Federal, state and local interests that have a role in the decision-making process. It was noted that the policies and objectives of the various agencies are often in conflict, and that even a traditional agency rivalry or interpersonal mistrust could hinder the acceptance of an innovative proposal.

Telephone interviews with representatives of various Federal and state agencies and with representatives of some architechture and engineering firms indicated that the institutional barriers identified in earlier reports still exist, although there are indications that attitudes may be changing. EPA's Innovative and Alternative (I/A) Technologies Program has been an important force in reshaping attitudes toward aquatic plant wastewater treatment systems. As described by Smith and Bastian (1979),

implementation of the EPA program involved increasing Federal funding for the design and construction of I/A technology projects (increased from 75 percent to 85 percent), a 15 percent cost-effectiveness preference for I/A technology over lower cost conventional technologies, 100 percent funding to modify or replace I/A technology facilities should they fail, and specific set-asides in state allotments of construction grant funds for I/A technology projects.

As a consequence of this kind of support, pilot aquatic plant wastewater treatment projects, predominately of the wetland or marsh/pond overflow system types, have been considered or actually constructed in many northern states. However, as reflected in the following summary of telephone interviews, there was a general skepticism regarding the suitability of most types of aquatic plant and wastewater treatment technologies in area's having cool seasons.

California: The State of California is committed to exploring the potential for use of aquaculture wastewater treatment systems, having established an Aquaculture Section in the Division of Planning and Research of the State Water Resources Control Board. As noted by Maughan (1979), this interest includes evaluating the potential for extending aquaculture wastewater treatment technologies into cooler areas of the state using greenhouse covers. An aquaculture specialist with the Water Resources Control Board, identified a number of projects that have been undertaken in the state (Inouye, personal communication). These include marsh and floating aquatic plant systems. A major pilot project, which is in the design phase, is planned for the San Diego area.

Illinois: State authorities have shown a guarded interest in aquatic plant wastewater treatment technologies. A representative of the Division of Water Pollution Control of the Illinois Environmental Protection Agency noted that two marsh type systems have been constructed in the state, one south of Carbondale and one near Decatur (Akers, personal communication). Although the simplicity of these systems was seen as attractive, the potential for performance failures during the winter months and lack of control have caused concern. Areas of current interest include the rush and reed type system developed in West Germany and the potential for cultivating algal growths on the bottom of lagoons for additional reduction of BOD and suspended solids.

Kentucky: State authorities do not foresee the use of aquaculture wastewater treatment systems in Kentucky. A representative of the Division of Water Quality of the Kentucky Department for Natural Resources and

Environmental Protection noted that the state is probably not far enough south to enable the effective use of these approaches (Baldwin, personal communication). NASA Technology Applications Program Office personnel expressed a belief that engineering firms within the state were reluctant to propose the use of aquatic plant systems in part because of lack of adequate exposure to the concept (Robinson, personal communication). Accordingly, NASA and the Society for Professional Engineers co-sponsored an aquaculture wastewater treatment seminar in Louisville during April 1981. Robinson anticipates that the representatives of engineering firms who attended that seminar will more closely examine opportunities for using innovative aquatic plant wastewater treatment technologies.

New York: Although several aquatic plant facilities have been contemplated or constructed in New York, authorities expressed a general concern about the usefulness of the approach in a cooler climate state. DiMura (personal communication) of the Division of Pure Waters of the New York State Department of Environmental Conservation (DEC) noted that a marsh/pond overland flow system, designed after the Brookhaven National Laboratory prototype, has been constructed in Orange County, New York. Wright (personal communication), the project manager for the engineering firm that designed the system, noted that legal and regulatory barriers have inhibited the development of other aquatic plant systems; for example, although a small, seasonal wetlands system operating at Kutcher's Hotel in Thompson, New York is considered successful, Federal and state regulations and policies regarding wetlands protection preclude the development of other similar systems.

Two floating aquatic plant systems were also discussed during the course of conversations with New York State Agency personnel. One was a duckweed facility which was considered, but abandoned because of anticipated problems with cool weather, and a second is an on-going project, designed after the Solar AquaCell System developed in California, and to be located in the community of Woodstock, New York (Dassatti, personal communication). The president of the firm contracted to design the facility noted that institutional problems have plagued the project (Lombardo, personal communication). The paucity of technical information available on the type of facility being planned has made regulatory approval difficult. Considering the range of Federal, state, and local agencies having jurisdiction over the project, it

was felt that a strong commitment by EPA (including an assumption of financial risk should the project fail) would be necessary to facilitate project development. Lombardo noted that the supportive attitude of the community of Woodstock has been mainly responsible for the continued progress of the project.

Pennsylvania: It is the policy of the State of Pennsylvania to encourage the use of innovative treatment technologies, especially for small communities in depressed areas. Carpenter (personal communication) of the Bureau of Water Quality Management of the Pennsylvania Department of Environmental Resources reported that the state is financing a demonstration facility in the village of Iselin (Indiana County), which is designed after the Brookhaven National Laboratory marsh/pond overland flow prototype system. It also was noted that a similar facility was constructed using private funds at a mobile home park in the King of Prussia area.

3.2 Effluent Regulations

The regulation of discharges by sewage treatment facilities is the joint responsibility of the Federal and state governments. In accordance with the Clean Water Act (33 U.S. Code 1251, et seq.), the EPA establishes minimum requirements for the treatment of discharges. Both the EPA and individual state agencies are authorized to establish more stringent requirements when necessary to protect the quality of public waters. The states vary in their approaches to effuent regulation. Some general trends are apparent, however, including a movement toward seasonally adjusted limitations based on the assimulative capacity of receiving waterbodies. In addition, an upcoming review of provisions of the Clean Water Act may lead to substantive changes in Federal wastewater treatment regulation. Representatives of several state agencies contacted in the course of this study expressed the belief that anticipated changes in the regulatory structure would favor the development and use of innovative approaches, such as aquatic plant wastewater treatment technology.

Presently, wastewater treatment facilities must, at a minimum, comply with requirements for secondary treatment. As detailed in the Code of Federal Regulations (Title 40, Part 133) the EPA has defined the minimum level of effluent quality attainable by secondary treatment in terms of three parameters: biochemical oxygen demand, suspended solids and pH. Specific requirements are given as:

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o Biochemical Oxygen Demand (five-day) and Suspended Solids*

-The arithmetic mean of the values for effluent samples collected in a period of 30 consecutive days shall not exceed 30 milligrams per liter.

-The arithmetic mean of the values for effluent samples collected in a period of 7 consecutive days shall not exceed 45 milligrams per liter.

-The arithmetic mean of the values for effluent samples collected in a period of 30 consecutive days shall not exceed the mean of the values for influent samples collected at approximately the same times during the same period (85 percent removal).

o pH

-The effluent values for pH shall be maintained within the limits of 6.0 to 9.0 unless the publicly owned treatment works demonstrates that: (1) Inorganic chemicals are not added to the waste stream as part of the treatment process; and (2) Contributions from industrial sources do not cause the pH of the effluent to be less than 6.0 or greater than 9.0.

The Clean Water Act specifies that by 1 July 1983, all publicly owned treatment works must provide for the application of "best practicable waste treatment technology". This has been interpreted as a mandate for more stringent effluent standards by 1983. However, both the U.S. Congress and EPA's Office of Water Program Operations have shown interest in examining the effects of present regultory policies and in considering alternatives to the present secondary treatment standards (Hais, personal communication). Thus, future Federal sewage treatment requirements and their effects on the development and use of innovative wastewater treatment technologies are presently uncertain.

The individual states are authorized by the Clean Water Act to impose effluent regulations more stringent than the secondary treatment standards promulgated by the EPA when necessary to protect water quality. Contact with personnel from the water quaity control agencies of five states indicated that most publicly owned sewage treatment facilities are required to meet no more than the Federal secondary treatment standards. In one state, Illinois, effluent limitations are generally more strict than those established by the EPA. The representatives of all five states noted that more stringent requirements, notably limitations of levels of ammonia

*The SS requirements for wastewater treatment ponds with a maximum facility design capacity of 2 MGD or less were revised on October 7, 1977 (40 FR 54666) to allow states to establish less stringent criteria than 30/30.

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nitrogen, have been imposed on some facilities. In most cases, these additional requirements are seasonally adjusted, with the most stringent limitations being imposed during the warmer months. In general, a trend was noted toward seasonally adjusted effluent limitations, based on the varying assimilative capacity of receiving waterbodies.

California: State requirements generally follow the Federal secondary treatment standards, with more stringent regulation of facilities discharging into sensitive waterbodies (Martinson, personal communication). More stringent requirements generally are adjusted seasonally.

Illinois: State regulations are more stringent than the Federal secondary treatment standards (Bridgewater, personal communication). For most treated effluents, levels of BOD_5 and suspended solids may not exceed 10 mg/l and 12 mg/l, respectively. Some facilities employing third-stage treatment lagoons are exempted from these regulations. Levels of ammonia nitrogen are regulated using a seasonal adjustment approach: levels up to 4.0 mg/l are permitted between 15 November and 15 April; levels up to 1.5 mg/l are permitted between 15 April and 15 November.

Kentucky: State regulations follow the Federal secondary treatment standards, although limitations on ammonia nitrogen and more stringent limitations on BOD_5 often are imposed (Baldwin, personal communication). Recently, an assimilative capacity approach has been adopted, allowing for a relaxation to secondary standards during cooler months.

New York: The State generally adheres to the Federal secondary treatment standards (Stevens, personal communication). At times, more lenient standards would be preferred. However, in some cases, the State exercises its authority to impose very strict requirements. For example, a 50 percent nitrification requirement has been imposed on some facilities discharging into water quality limited waterbody segments; and under low flow conditions, dischargers have been required to meet receiving waterbody water quality criteria: 5 mg/l BOD_5, 10 mg/l suspended solids, 2 mg/l ammonia, and at least 7 mg/l dissolved oxygen.

Pennsylvania: State regulations generally follow the Federal secondary treatment standards (Carpenter, personal communication). Limitations on ammonia levels have been imposed at some facilities. These are seasonally

adjusted, with the more stringent requirement of no more than 1.5 mg/l being specified during the warmer months (31 May to 1 October).

3.3 Regulations Pertaining to the Use, Sale and Transport of Exotic Plants

The development of certain types of aquatic plant wastewater treatment facilities in cooler U.S. states may involve the importation of plant species that are presently not found in those states. For example, the construction of a greenhouse-covered water hyacinth system in a state such as New York would require the transport of that plant from a state such as Florida. There are laws and regulations pertaining to the use, sale and transport of exotic plants. This issue has not been addressed in the literature on aquatic plant wastewater treatment. However, a preliminary investigation carried out as part of this study indicates that these laws and regulations may be an important barrier to the diffusion of certain aquaculture technologies.

One Federal law that may have important implications for the development of aquatic plant wastewater treatment systems is the Federal Noxious Weed Act of 1974 (7 U.S. Code 2801-2813). Section 2803 of the Act specifies that:

> "No person shall knowingly move any noxious weed, identified in a regulation promulgated by the Secretary, into or through the United States or interstate, unless such movement is authorized under general or specific permit form the Secretary (of Agriculture) ..."

The U.S. Department of Agriculture (USDA) has identified 25 plant species that are subject to these regulations, and is considering the regulation of about 50 others (Sand, personal communication). The USDA is mainly concerned about the importation of plant species from outside the U.S. None of the listed species has been used in an aquatic plant wastewater treatment system in the U.S. However, state governments may cite the Noxious Weed Act of 1974 as a basis for regulating interstate transport of species found within the U.S., but not within that state.

A second Federal law which may specifically affect the development of water hyacinth wastewater treatment facilities is entitled "Act to Amend Chapter 3 of Title 18 of the U.S. Code Relating to Animals, Birds and Fish" (18 U.S. Code 46). Under this Act, the interstate transport or sale of plants or seeds of water hyacinth (*Eichhornia crassipes*), alligator grass (*Alternathera philoxeroides*), or water chestnut (*Trapa natans*) is a Federal offense, punishable by a fine of $500, imprisonment of not more than six months, or both.

In general, however, state regulatory policies may have more influence than Federal policies on the development of aquaculture wastewater treatment facilities. Contacts with personnel from the regulatory agencies of five

states indicated that any proposal to import an aquatic plant presently not found in a given state would have to be carefully evaluated. In general, state authorities expressed concern that an imported species would accidently be released into the receiving waterbody; and would survive and reproduce at levels sufficient to create an ecological or navigational problem. Specific comments from state personnel were as follows:

California: USDA permit forms are used to evaluate requests for the importation of aquatic plant species presently not found in the State (Gray, personal communication). Water hyacinth already ranges into California. Thus, use of this plant for wastewater treatment probably would not be restricted. However, the importation of hydrilla, even for wastewater treatment applications, is strictly prohibited.

Illinois: Policies are very restrictive with regard to the importation of plant species presently not found within the State (Seaborg, personal communication). Admission of an exotic would be permitted only after filing a USDA permit from and adequate demonstration that no problems would occur as a result of importation.

Kentucky: Requests for the importation of plant species presently not found within the State are made using the USDA permit form. These requests are evaluated by the the State Entomologist. Some requests to import exotic plants have been denied (Pass, personal communication). In general, arguments for importation based on claims that a species would be unable to survive winter temperatures are considered questionable.

New York: Several aquatic plant species have created navigational problems in New York waterways; thus, State authorities would prefer not to introduce any new species (Skinner, personal communication). The USDA permit form would be used to evaluate any proposal to import an exotic aquatic plant.

Pennsylvania: The USDA permit form is used to evaluate requests for the importation of aquatic plants presently not found in the State (Forer, personal communication). The permit process is not viewed as a means of prohibiting importation, but rather as a way of safeguarding against errors.

4.0 COST CONSTRAINTS

As discussed in previous sections, the use of aquatic plant systems in cooler climates probably would require some form of climate control, such as a greenhouse. The concern, as expressed by Middlebrooks and Reed (1981), is that the additional costs of a greenhouse would be so high that aquatic plant systems would not be economically feasible when compared to conventional treatment alternatives. This section presents a preliminary evaluation of this issue, through the expansion of earlier studies on the cost effectiveness of aquatic plant wastewater treatment systems. Overall, it was found that aquatic plant systems in a greenhouse would probably be cost competetive with conventional systems only at smaller plant scales (e.g., 0.1-MGD facilities) and only if innovative approaches are used to reduce heating costs.

4.1 Costs of Systems Without Climate Control

Several investigators have calculated generalized cost estimates for aquatic plant wastewater treatment systems and have compared these costs with the costs of conventional treatment systems. Overall, these preliminary analyses indicate that in warmer climates both floating aquatic plant and artifical wetland systems are cost-competetive with conventional treatment alternatives.

In their analysis of resource requirements and cost elements of various treatment systems, Tchobanoglous et al. (1979a) reported that both water hyacinth and artifical wetland systems were cost-competetive with two commonly used conventional systems for meeting secondary treatment standards. The aquatic plant systems that were considered included pretreatment options of either conventional primary treatment or facultative ponds. As shown on Table 3, construction costs for aquatic plant systems with primary treatment (screening and settling) were substantially lower than those for an activated sludge or a trickling filter facility designed to meet the same treatment requirements. However, land requirements for the aquatic plant systems were substantially higher.

In another general economic analysis, Crites (1979) found that water hyacinth and wetland treatment systems were less costly than conventional alternatives for both advanced secondary and advanced (nutrient removal) wastewater treatment. For advanced secondary treatment, defined as 10 mg/l limitations for BODs and suspended solids and a 200 MPN/100 ml limitation

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TABLE 3

RESOURCE REQUIREMENTS AND COST ESTIMATES FOR SELECTED AQUACULTURE AND CONVENTIONAL 1 MGD WASTEWATER TREATMENT SYSTEMS

System	Land Required (acres)	Total Construction Costs* ($ x 10^6)	Labor Required (person hours/year)	Parts and Supplies Costs ($/year)
Water Hyacinth (with primary treatment)	21.5	0.830	4,000	8,000
Water Hyacinth (with facultative pond)	50.0	1.730	5,500	13,000
Artifical Wetland (with primary treatment)	41.5	0.900	3,000	6,000
Artifical Wetland (with facultative pond)	70.0	1.800	4,500	11,000
Conventional Activated Sludge	4.0	1.600	5,500	16,000
Conventional Trickling Filter	5.0	1.700	4,200	14,000

*The cost of land is not included.

Source: Tchobanoglous et al. 1979.

for fecal coliforms, estimated total costs* for a 1-MGD plant were: $0.45 to $0.74/1,000 gallons for a water hyacinth system with an oxidation pond; $0.50 to $0.90/1,000 gallons for a wetland system with an oxidation pond; and $1.30/1,000 gallons for a conventional activated sludge system followed by dual media filtration. Based on these estimates, treatment using water hyacinths would cost as little as one-third as much as a conventional treatment approach.

Costs for advanced treatment, defined as advanced secondary levels plus a 3 mg/l limitation for total nitrogen and a 1 mg/l limitation for total phosphorus also were estimated by Crites (1979). In this case the estimated total cost of a hybrid 1-MGD facility consisting of overland flow and water hyacinth systems was $0.79/1,000 gallons. Costs for comparable treatment using conventional systems was reported as $2.49/1,000 gallons. In an earlier study and using a different set of assumptions, Robinson et al. (1976) estimated costs for the same treatment level. Costs for a water hyacinth system and a conventional treatment system were reported as $1.22/1,000 gallons and $0.89/1,000 gallons, respectively.

4.2 Additional Costs of Greenhouse Use

In many regions of the U.S. some form of climate control probably would be required to ensure the reliable year-round performance of aquatic plant wastewater treatment systems. Climate control refers to actions which alter and maintain climate at a state different from its natural or uncontrolled state (MacKinnon 1978). For horticultural enterprises, climate control is typically accomplished using some form of greenhouse. The costs of greenhouses are highly variable, depending upon local climatic conditions, design and materials used. In the special case of aquatic plant wastewater treatment systems, there may be opportunities to defray partially the operating costs through use or sale of harvested plants. However, as discussed below, the costs of using a greenhouse are substantial and may discourage the selection of this technology in many cases.

There are many types of greenhouse designs, representing a wide range of capital and maintenance costs. Two designs that are commonly used in commercial operations are the span-type greenhouse and a modification called the ridge-and-furrow house. The span design is based on a rectangular floor plan, where the sides of the roof are of equal height. The center of the ridge of the structure is generally 15 to 20 feet high, and the rafters slope down to the sides about 8 feet above the ground. The ridge-and-furrow design involves joining two or more span houses along the side wall. Wood or light-weight aluminum are typically used for framing; and glass, fiberglass or various plastic materials are used for glazing. Other major construction cost components include ventilation and heating systems, which may be electric or fossil fuel powered.

*Total costs included amortized capital costs, operating and maintenance costs and land costs.

According to representatives of two major commercial greenhouse contractors in the U.S., total construction costs for standard greenhouses range from $15 to $40/square foot of floor space (Curtin, personal communication; Pastor, personal communication). These estimates include the costs of ventilation and heating systems. It was noted that a polyethylene cover system could be installed at a much lower cost, approximately $3 to $4/square foot of floor space. However, these systems are less effective and less durable over the long term. Fuel (natural gas) costs for heating during cooler months were estimated to range from $1 to $2/square foot of floor space per month, depending upon local climatic conditions.

To estimate the additional costs of using a greenhouse for an aquatic plant wastewater treatment system, it was also necessary to determine the amount of area to be enclosed. For 1-MGD water hyacinth systems, Crites (1979) concluded that between 5 and 10 acres of pond area would be required, depending upon local conditions. Middlebrooks and Reed (1981) reported that hyacinth systems processing a secondary effluent can be designed to handle 2,000 m^3/ha/day, if the prinicpal objective is control of BOD_5 and suspended solids in the effluent. This hydraulic loading rate roughly equates to a 5 acre pond area requirement for a 1-MGD facility. Based on these studies, it was concluded that a 0.1-MGD facility would involve enclosing a 0.5 acre area, and a 1-MGD facility would involve housing a 5 acre area.

The information presented above was used to expand the cost comparison study carried out by Tchobanoglous et al. (1979a). As shown in Table 4, a water hyacinth system in a greenhouse would be substantially more costly than conventional treatment systems. It is notable that the differences in cost are most pronounced for larger capacity treatment facilities. However, even small capacity plant scales, construction costs for aquatic plant systems in a greenhouse would probably be at least 50 percent higher than those for conventional systems. However, costs associated with heating the greenhouse enclosure would increase annual costs far beyond those typically incurred for wastewater treatment. It is important to note that recent innovations in "solar" greenhouse design have resulted in substantial savings in fuel costs (Ruttle 1978). As noted by Middlebrooks and Reed (1981) methane produced from harvested plants might be used to heat greenhouse enclosures, thereby offsetting anticipated fuel costs.

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TABLE 5

COST COMPARISON OF WATER HYACINTH AND SELECTED CONVENTIONAL WASTEWATER TREATMENT SYSTEMS REFLECTING ADDITIONAL COSTS OF GREENHOUSING

System/Cost Component	0.1 MGD Scale Plants		1.0 MGD Scale Plants	
	Construction Costs ($ x 10^6)	Parts and Supplies Costs ($/year)	Construction Costs ($ x 10^6)	Parts and Supplies Costs ($/year)
Water Hyacinth (With primary treatment)				
Base[a]	0.331	3,500	0.830	8,000
Additional for Greenhousing[b]	0.871	87,120	3.267	871,200[c]
TOTAL	1.202	90,620	4.097	879,200
Conventional Activated Sludge TOTAL[a]	0.710	8,000	1.600	16,000
Conventional Trickling Filter TOTAL[a]	0.732	6,000	1.700	14,000

[a]Cost estimates reported in 1979 dollars by Tchobanoglous et al. (1979). Construction costs do not include land costs.

[b]Cost estimates reported in 1981 dollars, based on greenhouse data provided by commercial greenhouse manufacturers (Curtin, personal communication; Pastor, personal communication) and on acreage requirements reported by Crites (1979) and Middlebrooks and Reed (1981).

[c]Estimated natural gas costs for greenhouse heating during four months of the year.

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5.0 SUMMARY AND CONCLUSIONS

In general, the results of this study indicate that there are several barriers to the use of higher aquatic plants for municipal wastewater treatment in cooler climates. As detailed below, major concerns are the temperature requirements of many of the species that are presently used in aquatic plant systems, certain legal and regulatory constraints, and the high construction and operating costs associated with climate control. It is important to note that current and future research and development activities may substantially alter this outlook. A number of concepts that could enhance opportunities for cooler climate applications of this innovative technology are discussed in the recommendations. Concepts, such as, land treatment, the use of winter storage and the use of peat bogs were beyond the scope of this study.

- o Reliable year-round performance by aquatic plant wastewater treatment systems without climate control is likely only in southern portions of the continental U.S. (to a latitude of about 35°N) and in Hawaii, Puerto Rico and the Virgin Islands.

  - Water hyacinth systems probably would be successful only in areas where the average daily temperature is a least 15°C (59°F), such as southern Florida, the southern tip of Texas and in Hawaii.

  - Emergent or wetland species may be effective at cooler temperatures (i.e., average daily air temperature at least 10°C (50°F). Recent studies indicate that those species having extensive rhizome systems may be particularly well suited for cooler climate applications. However, most studies on contaminant removal by wetland species have involved the use of associations of a number of species in a natural or artificial wetland setting. The complexity of such systems makes it difficult to identify the effectiveness and cold-temperature tolerances of individual species.

  - Some duckweed species may be capable of removing contaminants at temperatures as low as 7 to 10°C (45 to 50°F). This suggests that duckweed wastewater treatment systems may have the highest potential for applications in cooler climates. The estimated zone of utility extends northward in the continental U.S. to a latitude of 35°N.

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- The use of aquatic plant treatment technology in cooler climates (north of 35°N latitude) probably would necessitate the use of a greenhouse. The additional construction and operating costs of greenhouse use would increase total costs substantially above those for conventional treatment alternatives.

  - Construction costs for a 0.1-MGD water hyacinth system designed to meet advanced secondary treatment standards would increase from about $133,000 to $1,202,000, with the addition of a standard, rigid structure greenhouse. Construction costs of conventional treatment alternatives would be $170,000 to $732,000.

  - Parts and supplies costs for a 0.1-MGD water hyacinth system would increase from about $3,500 per year to $90,600 per year, with the addition of greenhouse heating fuel requirements. Parts and supplies costs for conventional treatment alternatives range from $6,000 to $8,000 per year.

  - Cost increases would be accentuated at larger facility scales.

- A wide range of Federal and States statutes and regulations apply to municipal wastewater treatment. While some recent developments in this area may favor the use of aquatic plant wastewater treatment technology, a number of legal and regulatory barriers to technology diffusion were identified.

  - Regulatory personnel from five temperate climate states indicated that wetland or marsh/pond overflow systems may be suitable for cooler climate areas. In general, they were skeptical regarding the potential usefulness of other types of aquatic plant systems.

  - Regulations governing municipal wastewater discharges are being reviewed and modified. Some trends, including a movement toward seasonally adjusting limitations based on the assimilative capacity of receiving waters, may favor the use of aquatic plant treatment alternatives.

  - Laws restricting the use, sale and transport of exotic plants within the U.S. may prevent the use of some plants for wastewater treatment in cooler climate states.

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6.0 RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOMENT ACTIVITIES

In the course of this study, a number of concepts that could accelerate the development of aquatic plant wastewater treatment systems were identified. These ideas, grouped into five categories, are identified and briefly described below.

6.1 Seasonal Facility Operation

This study indicates that during the warmest six months of the year some aquatic plant systems probably would be effective in wastewater treatment throughout most of the U.S. Accordingly, aquatic plant systems may be well suited for use by summer recreational communities. This concept has been tested successfully. A project involving the use of bulrushes in a recreational community setting in the Netherlands was reported to be cost-effective (de Jong 1976). Successful projects in the U.S. include a natural wetlands system employed at Kutcher's Hotel, a summer resort in New York State.

In addition to the summer community application, aquatic plant systems could be attached to existing conventional treatment systems to meet the more stringent effluent limitations that some states are imposing during summer months. In this case, a small greenhouse facility could be constructed to overwinter seed plant stock. Natural systems, utilizing indigenous wetland plants and storage of wastewater over the winter months, could also extend aquatic treatment systems to cooler climates.

6.2 Concepts Relating to Climate Control

Several concepts relating to climate control and aquatic plant wastewater treatment have been developed by other investigators. For example, Dinges (personal communication) suggested that spraying wastewater, which is typically warmer than ambient air temperature, over the leaves of floating aquatic plants, could slightly extend the use of these systems into cooler areas.

With regard to greenhouses, there is evidence that the high costs of heating an enclosure could be reduced or mitigated. As discussed by Ruttle (1978) advances in passive solar greenhouse design can substantially reduce (e.g., by 30 percent) fuel costs. Middlebrooks and Reed (1981) discuss the alternative of using methane produced from harvested plants to heat a greenhouse enclosure. Production of methane from harvested water hyacinths is a major element of research being conducted at the Disney World facility in Lake Buena Vista, Florida. Results of this research should provide important insights regarding the potential for reducing greenhouse heating

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costs. Other concepts that have been suggested include the use of geothermal energy and waste heat utilization (e.g., power plant discharges). These concepts probably would be widely applicable.

6.3 Species Selection

Although a number of plant species have been identified as potential candidates for wastewater treatment applications, very little is known about their temperature requirements. Thus, it is likely that additional investigation will result in the identification of genera, species and even strains of plants that would be effective in removing contaminants at lower temperatures. For example, Hillman and Culley (1978) concluded that a strain of duckweed that would grow rapidly at 5 to 10°C could be identified through an intensive selection program.

A more complete understanding of the performance of various species over a range of temperatures could be helpful in developing a program of species rotation over the course of a year. For example, a plant species with a high temperature requirement, such as water hyacinth, could be used during summer months; while a cold-tolerant strain of duckweed could be used during cooler months.

6.4 Development of Related Technologies

One aspect of an innovative technology that is especially difficult to assess is its ramifications over time. Several of the researchers working with aquatic plant treatment technology have demonstrated a vision of the possible long-term benefits that could accrue from use of this technology.

One basic technical concept involves the potential for linking an aquatic plant treatment approach with other treatment approaches. For example, the new NASA Hybrid System combines anaerobic filters with a trough planted with Phragmites to produce a synergistic treatment effect (Wolverton 1981). Wolverton (personal communication) also is investigating the potential for linking food production facilities to treatment systems. As noted previously, the Disney World project includes an investigation of the potential for linking methane production to the treatment process. Considering these opportunities, the cost-effectiveness of aquatic plant wastewater treatment technology may change dramatically over the next few years.

6.5 Concepts Related to Legal and Regulatory Barriers

As noted by Eichbaum (1976) regulatory offices often lack personnel with the kinds of training that would permit an adequate evaluation of the concepts and opportunities inherent in an innovative wastewater treatment technology. Robinson (personal communication) added that private engineering firms often lack the kinds of expertise required to develop a sound design for an aquatic plant wastewater treatment facility. Thus, one important step toward the development of aquatic plant systems in cooler

climate states may be the consolidation and dissemination of available information on this innovative technology. This could be accomplished by alerting state regulatory authorities to the availability of recent studies on aquatic plant wastewater treatment and by the conduct of informative seminars. One important topic would be the potential for aquatic plant wastewater treatment in states having seasonally adjusted discharge limitations.

The effects of laws governing the use, sale and transport of exotic plants on the development of aquatic plant wastewater treatment systems may be an important topic for detailed investigation. Many of the plant species that are most commonly used in wastewater treatment facilities are not presently found in the cooler climate states. The use of these species would require a demonstration that their introduction would not have adverse environmental effects. Important areas of investigation are the overwintering potential of candidate plant species, and the potential for confining the aquatic plants within a facility.

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